***New Phytologist* Supporting Information**

Article title: Mycorrhizal associations change root functionality: a 3D modelling study on competitive interactions between plants.
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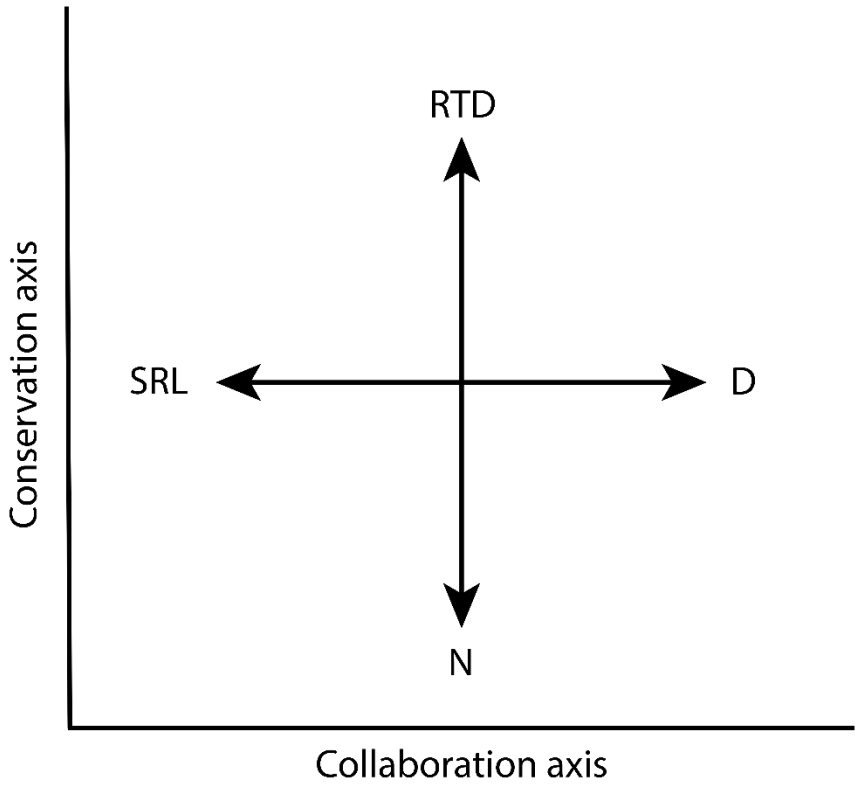

Fig. S1. Schematic representation of the two-dimensional root economic space framework as presented in Bergmann *et al.* (2020). The so called 'conservation' axis is characterised by a trade-off between root tissue density (RTD) and root nitrogen content (N). Plants that grow fast have a high N, but low RTD; slow growing plant species have generally opposite characteristics. The collaboration axis is characterised by a trade-off between SRL and root diameter (D). Plant species that employ a 'do-it-yourself' strategy of nutrient acquisition have a high SRL and low D; outsourcing species have a large root diameter, because the symbiosis requires space in the root cortex and a low SRL.

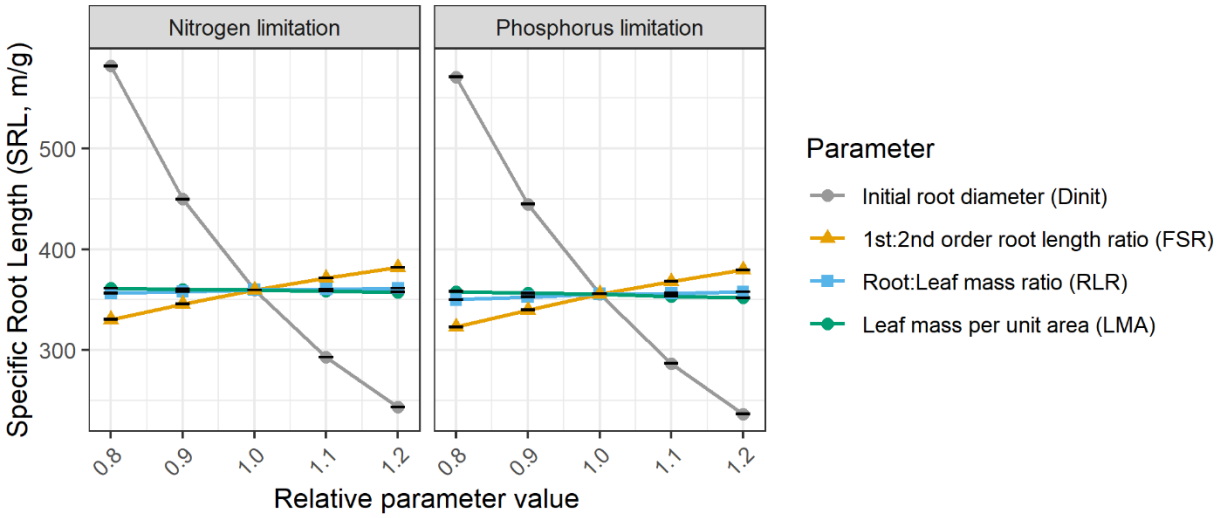

Fig. S2. Specific root length (SRL, m g^{-1}) as a function of relative parameter changes in the initial root diameter (grey circles), 1^{st}:2^{nd}-order root length ratio (yellow triangles), Root:Leaf mass ratio (blue squares) or leaf mass per unit area (green circles) under either nitrogen (left) or phosphorus (right) limiting conditions. Error bars show the standard error of the means.

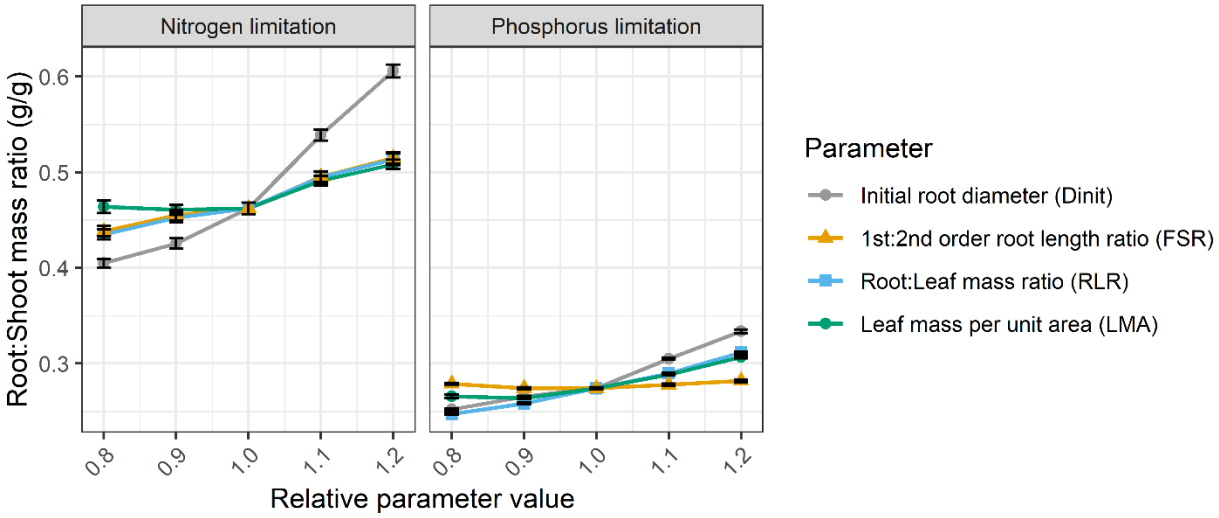

Fig. S3. Root:Shoot mass ratio (g g^{-1}) as a function of relative parameter changes in the initial root diameter (grey circles), 1^{st}:2^{nd}order root length ratio (yellow triangles), Root:Leaf mass ratio (blue

squares) or leaf mass per unit area (green circles) under either nitrogen (left) of phosphorus (right) limiting conditions. Error bars show the standard error of the means.

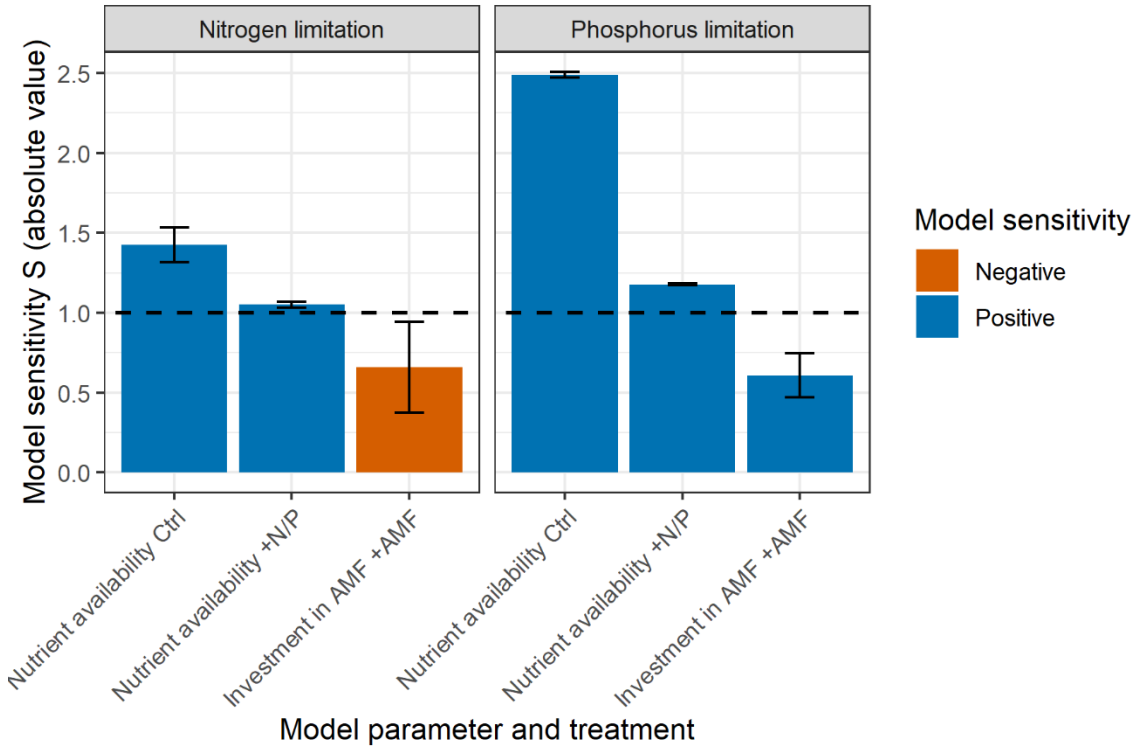

Fig. S4. Model sensitivity S (absolute value, see eq. 1) of the nutrient availability (in monostands) and the investment in AMF (in mixtures with AMF) under either nitrogen (left) or phosphorus (right) limiting conditions. The model sensitivity is defined as the relative effect of a parameter change on individual plant biomass (y-axis shows absolute values of model sensitivity S, see eq. 1), with the dotted line representing a model sensitivity of one, e.g. where a parameter change shows a 1:1 proportional effect. Values above that line indicate disproportionally strong effects whereas values below that line indicate disproportionally small effects. A negative sensitivity (red) indicates that an increase in a parameter value leads to a decrease in individual plant biomass. A positive sensitivity (blue) indicates that an increase in a parameter value leads to an increase in individual plant biomass. Error bars show the standard error of the means.

Table S1: Indices used in the model description.

Index	Name	Index	Name
l	Leaf	*a*	Apical root segment
R	Root system	*na*	Non-apicalroot segment
o	Plant organ	*i*	Nutrient
r	Root segment	*N*	Nitrogen
3	3rd-order root	*P*	Phosphorus
2	2nd-order root	*c*	Soil cell
1	1st-order root	*AMF*	Arbuscular mycorrhizal fungi

Table S2. List of the model parameters, their values and units.

Parameter	Description	Value	Unit	Eq.
RLR	Root:leaf ratio	1[a]	g g^{-1}	S1
IBD	Inter branch distance	0.0078[b]	m	
Dinit	Initial root diameter	0.0011[b]	m	S3
D23	Ratio between 2nd-order and 3rd-order root diameters	0.5[b]	m m^{-1}	S3
D12	Ratio between 1st-order and 2nd-order root diameters	0.375*	m m^{-1}	S4
EL	Slope of potential root elongation rate vs root diameter	18[b]	m m^{-1} day^{-1}	S5
TD_r	Root tissue density	$5*10^4$ [b]	g m^{-3}	S5,6,9,10
fAMF	AMF:root mass ratio	0.063[c]	g g^{-1}	S5,7,9,10
FSR	1st:2nd-order root length ratio	40	m m^{-1}	S6
ur_N	Uptake radius for nitrogen	0.03	m	S11,14
ur_P	Uptake radius for phosphorus	0.001[d,e]	m	S11,14
RHL	Root hair length	0.001	m	S11
$Cmin_{N,r}$	Minimum nitrogen concentration required for root uptake	2[f]	µMol L^{-1}	S12
$Cmin_{P,r}$	Minimum phosphorus concentration required for root uptake	1.2[g]	µMol L^{-1}	S12
D_{AMF}	Diameter of AMF hyphae	$5*10^{-6}$	m	S13,14
TD_{AMF}	Tissue density of AMF hyphae	$22*10^4$ [h]	g m^{-3}	S13
$Cmin_{N,AMF}$	Minimum nitrogen concentration required for AMF uptake	2**	µMol L^{-1}	S15
$Cmin_{P,AMF}$	Minimum phosphorus concentration required for AMF uptake	0.3[g]	µMol L^{-1}	S15
$nmin_N$	Leaf nitrogen concentration at which photosynthetic capacity is zero	0.0053[i]	g g^{-1}	S16,19
$nmin_P$	Leaf phosphorus concentration at which photosynthetic capacity is zero	0.000353***	g g^{-1}	S16,19
$Amax_0$	Maximum photosynthetic capacity of a leaf	35	µMol m^{-2} s^{-1}	S19
$nmax_N$	Leaf nitrogen concentration at which photosynthetic capacity is maximised	0.053[i]	g g^{-1}	S19
$nmax_P$	Leaf phosphorus concentration at which photosynthetic capacity is maximised	0.00353***	g g^{-1}	S19

[a] Müller *et al.* (2000); [b] Pagès *et al.* (2014); [c] Jakobsen and Rosendahl (1990); [d] Gahoonia and Nielsen (1997); [e] Li *et al.* (1991); [f] York *et al.* (2016); [g] Silveira and Cardoso (2004); [h] Fogel and Hunt (1979); [i] Yin and van Laar (2005)

* Assuming 1st-order roots are comprised of two additional root orders with an average diameter of (0.5*0.25)/2 = 0.375 according to the model of Pagès *et al.* (2014). The resulting 1st-order root diameter (D_T = 0.206 mm) is larger than the minimum root diameter reported for pea in Pagès *et al.* (2014) (D_{min} = 0.19 mm).

**Assumed equal to the minimum nitrogen concentration required for root uptake.

***Assuming an optimal N:P ratio of 15:1 in plant tissues (Aerts & Chapin III, 1999).

Methods S1

Carbon allocation to the root system

One of the primary functions of the root system is to provide the plant with water and nutrients. These resources are (among other functions) necessary to maintain photosynthesis, functionally tying the root system to the leaves. Therefore, we assume that the potential growth rate of the root system ($Sink_R$, g day^{-1}) is dependent on total leaf biomass ($\sum_{l=1}^{nl} Bio_l$, g), the root system's biomass (Bio_R, g), a parameter that describes the desired ratio between root and leaf biomass (RLR, g g^{-1}), and the time step (t, one day).

$$Sink_R = \frac{\left(\sum_{l=1}^{nl} Bio_l * RLR - Bio_R\right)}{t} \quad \text{(S1)}$$

The amount of carbon allocated to the root system (Ca_R, g day^{-1}) is dependent on the potential growth rate of the root system relative to the total potential growth rate of all plant organs ($\sum_{o=1}^{no} Sink_o$, g day^{-1}), and is either limited by the potential growth rate of the root system ($Sink_R$, g day^{-1}), or the amount of carbon available for growth (Ca, g day^{-1}).

$$Ca_R = \min\left(Sink_R, Ca * \frac{Sink_R}{\sum_{o=1}^{no} Sink_o}\right) \quad \text{(S2)}$$

Root architectural model

The root architectural model is based on the ArchiSimple model described in Pagès *et al.* (2014), and uses pea as a model root system for the generic annual dicotyledonous species used in this study (model parameters taken from Pagès *et al.* (2014)). The 3rd-order root (index *3*) is the first root to emerge from the seed kernel upon germination. The 2nd-order roots (index *2*) are the lateral roots that emerge at fixed intervals (inter-branch distance, *IBD*, m) along the 3rd-order root. The 3rd and 2nd-order roots together make up the skeleton of the root architecture and are explicitly represented by root segments (index r, see Fig. 1) in the simulated 3D environment of the model. The 1st-order roots (index *r3*) are the finest roots that emerge from the 2nd-order roots. These 1st-order roots are assumed to extend equally in all directions and are represented

numerically as part of a non-apical 2nd-order root segment. The root segments at the tips of 3rd and 2nd-order roots are called apices (index *a*), and contribute to the growth of the root system through the elongation of the 3rd and 2nd-order roots. The rest of the 3rd and 2nd-order root system is made up of fully elongated non-apical root segments, with the non-apical segments on 2nd-order roots (index *na*) also contributing to the growth of the root system through the growth of 1st-order root biomass. See Table S1 for a full list of indices used in the model description.

The diameter of the 3rd-order root apex (D_{a3}, m) determines the diameter of its lateral 2nd-order root apices (D_{a2}, m) through parameters that denote the ratio between 2nd and 3rd-order root diameters (*D23*, m m^{-1}).

$$D_{a2} = D_{a3} * D23 \quad \text{(S3)}$$

Similarly, the diameter of the 2nd-order root apex (D_{a2}, m) determines the diameter of its lateral 1st-order roots (D_{r1}, m) through a parameter that denote the ratio between 2nd and 1st-order root diameters (D12, m m^{-1}).

$$D_{r1} = D_{a2} * D12 \quad \text{(S4)}$$

The growth potential of an apex (G_a, g day^{-1}) is a function of the root diameter (D_a, m) an elongation parameter (*EL*, m elongation m^{-1} root diameter day^{-1}), the root tissue density (TD_r, g m^{-3}), and a mycorrhizal allocation parameter (*fAMF*, g g^{-1}).

$$G_a = \left(D_a * EL * \pi \left(\frac{D_a}{2}\right)^2 * TD_r\right) * (1 + fAMF) \quad \text{(S5)}$$

The growth of 1st-order roots from a non-apical second order root segment is limited by a maximum 1st-order root biomass ($maxBio_{na2,1}$, g) that is determined by the 1st:2nd-order root length ratio (*FSR*, m 1st-order root length m^{-1} 2nd-order root length), the length the 2nd-order root segment (L_{na}, m), the 1st-order root diameter (D_1, m) and the root tissue density (TD_r, g m^{-3})

$$maxBio_{na2,1} = FSR * L_{na} * \pi \left(\frac{D_1}{2}\right)^2 * TD_r \quad \text{(S6)}$$

The growth potential of a non-apical 2nd-order root segment (G_{na2}, g day^{-1}) is determined by the difference between the root segment's current 1st-order biomass ($Bio_{na2,1}$, g) and its maximum 1st-order root biomass ($maxBio_{na2,1}$, g), a mycorrhizal allocation parameter ($fAMF$, g g^{-1}), and the time step (t, one day).

$$G_{na} = \left(maxBio_{na2,1} - Bio_{na2,1}\right) * (1 + fAMF) * \frac{1}{t} \quad \text{(S7)}$$

The carbon available for the growth of the root system (Ca_R, g day^{-1}) is then distributed over the root segments (Ca_r, g day^{-1}), according to their relative growth potential ($G_r/\sum G_r$).

$$Ca_r = Ca_R * \frac{G_r}{\sum_{r=1}^{nr} G_r} \quad \text{(S8)}$$

The elongation of an apex (dL_a, m day^{-1}) is determined by the amount of carbon allocated to the apex (Ca_a, g day^{-1}), the mycorrhizal allocation fraction ($fAMF$, g g^{-1}), the diameter of the root (D_r, m) and the root tissue density (TD_R, g m^{-3}).

$$dL_a = \frac{Ca_a * (1 - fAMF)}{TD_r * \pi \left(\frac{D_a}{2}\right)^2} \quad \text{(S9)}$$

The growth of 1st-order root length from non-apical 2nd-order root segments ($dL_{na2,1}$, m day^{-1}) is determined by the amount of carbon allocated to the non-apical 2nd-order root segment (Ca_{na2}, g day^{-1}), the AMF:root mass ratio ($fAMF$, g g^{-1}), the diameter of the 1st-order roots (D_1, m) and the root tissue density (TD_r, g m^{-3}).

$$dL_{na2,1} = \frac{Ca_{na2} * (1 - fAMF)}{TD_r * \pi \left(\frac{D_1}{2}\right)^2} \quad \text{(S10)}$$

Nutrient uptake by the roots

The soil volume exploited by a root is calculated differently for nitrogen and phosphorus due to their differences in solubility. We assume that 3rd-, 2nd- and 1st-order root length all contribute to

phosphorus uptake and that the phosphorus uptake radius is extended by the root hair length (Gahoonia & Nielsen, 1997). Conversely, the nitrogen depletion zone around a root is expected to extend far beyond the root hairs and even the 1st-order roots due to the higher mobility of nitrogen in the soil. Therefore, we assume that only 3rd- and 2nd-order root length contributes to the uptake of nitrogen (see Table S2).

The soil volume of nutrient *i* exploited by a growing root *r* ($dEV_{i,r}$, m^3 day^{-1}) is therefore dependent on only the growth of apices for nitrogen uptake (dL_a, m day^{-1} *if i=N*) or growth of both apices and 1st-order roots for phosphorus uptake (dL_a *and* $dL_{an2,1}$, m day^{-1} *if i=P*). Soil exploitation is further dependent on the uptake radius of nutrient *i* (ur_i, m), the root diameter (D_a or D_T, m), and for phosphorus uptake also on the root hair length (*RHL*, m).

$$dEV_{N,a} = dL_a * \pi \left(ur_N + \frac{D_a}{2} \right)^2 \quad \text{if i=N} \quad \text{(S11)}$$

$$dEV_{P,a} = dL_a * \pi \left(ur_P + RHL + \frac{D_a}{2} \right)^2 \quad \text{if i=P}$$

$$dEV_{P,na} = dLT_{an} * \pi \left(ur_P + RHL + \frac{D_t}{2} \right)^2 \quad \text{if i=P}$$

The uptake of nutrient *i* by root segment *r* ($U_{i,r}$, µMol day^{-1}) is then equal to the amount of nutrient *i* available in the soil volume exploited by the root, which is calculated by the amount of nutrient *i* present in soil cell *c* ($C_{i,c}$, µMol), the minimum uptake concentration of roots for nutrient *i* ($Cmin_{i,r}$, µMol m^{-3}) and the volume of the soil cell (V_c, m^3), the newly exploited soil volume by the root ($dEV_{i,r}$, m^3 day^{-1}) and the volume of the soil cell that is not yet exploited (UV_c, m^3), assuming optimal placement of roots in the soil volume.

$$U_{i,r} = (C_{i,c} - Cmin_{i,r} * V_c) * \frac{dEV_{i,r}}{UV_c} \quad \text{(S12)}$$

Nutrient uptake by mycorrhizal fungi

The model conceptualises the AMF as a very fine extension of the root system (analogous to the 1st-order roots in both theory and model implementation) that takes up nutrients from the same

soil cell as the root but may allow the plant to take up nutrients from outside of the rhizosphere (Li *et al.*, 1991). Like the roots, the mycorrhizal hyphae are assumed to take up all the nutrients within the nutrient uptake radius in a single time step. The growth in AMF hyphae length associated to root segment *r* ($dL_{r,AMF}$, m day^{-1}) is determined by the carbon allocation to root segment *r* (Ca_r, g day^{-1}) and the AMF:root mass ratio (*fAMF*, g g^{-1}), diameter of AMF hyphae (D_{AMF}, m) and the tissue density of AMF hyphae (TD_{AMF}, g m^{-3}).

$$dL_{r,AMF} = \frac{Ca_r * fAMF}{TD_{AMF} * \pi \left(\frac{D_{AMF}}{2}\right)^2} \quad \text{(S13)}$$

The soil volume of nutrient *i* exploited by the AMF hyphae associated to root segment r ($dEV_{i,r,AMF}$, m^3 day^{-1}) is calculated with the growth in AMF hyphal length ($dL_{r,AMF}$, m day^{-1}), the uptake radius of nutrient *i* (ur_i, m), and the diameter of AMF hyphae (D_{AMF}, m).

$$dEV_{i,r,AMF} = dL_{r,AMF} * \pi \left(ur_i + \frac{D_{AMF}}{2}\right)^2 \quad \text{(S14)}$$

The amount of nutrient *i* taken up by root segment *r* through the AMF mutualism ($U_{i,AMF}$, µMol day^{-1}) is then equal to the amount of nutrient *i* available in the soil volume exploited by the AMF, which is calculated by the amount of nutrient *i* present in soil cell *c* ($C_{i,c}$, µMol), the minimum uptake concentration of AMF for nutrient *i* ($Cmin_{i,AMF}$, µMol m^{-3}) and the volume of the soil cell (V_c, m^3), the newly exploited soil volume by the AMF ($dEV_{i,AMF}$, m^3 day^{-1}) and the volume of the soil cell that is not yet exploited (UV_c, m^3).

$$U_{i,r,AMF} = (C_{i,c} - Cmin_{i,AMF} * V_s) * \frac{dEV_{i,r,AMF}}{UV_c} \quad \text{(S15)}$$

Nutrient allocation in the plant

The pool of nutrient *i* that is available for photosynthesis (pN_i, g) is determined by the current pool of nutrient *i* (N_i, g) , the total uptake of nutrient *i* by root segment *r* and its associated AMF $U_{i,r}$, and $U_{i,r,AMF}$, µMol day^{-1}) during time step *t*, which is converted from µMol to grams with the

molar mass of nutrient *i* (*M(i)*, g Mol^{-1}), and the nutrient construction costs of new biomass in the plant, which is calculated with the growth of the plant (*G*, g) and the minimum concentration of nutrient *i* in plant biomass ($nmin_i$, g g^{-1}).

$$pN_i = N_i + \sum_{r=1}^{nr} \left(U_{i,r} + U_{i,r,AMF}\right) * t * M(i) * 10^{-3} - G * nmin_i \quad \text{(S16)}$$

The pool of nutrient *i* that is available for photosynthesis (pN_i, g) is then distributed over the leaves based on their relative nutrient requirement ($NSink_l$, g), which scales with leaf biomass (Bio_l, g) and the leaf's relative light interception ($relPAR_l$, dimensionless), which is modelled after the relation between light interception and photosynthetic capacity described in Anten *et al.* (1995). We assume that the plants are able to fully re-distribute these nutrient pools among the leaves within a single time step.

$$NSink_l = Bio_l * relPAR_l^{0.4} \quad \text{(S17)}$$

The amount of nutrient *i* allocated to the photosynthetic capacity of leaf *l* ($pN_{i,l}$, g) is determined by the pool of nutrient *i* that is available for photosynthesis (pN_i, g), the nutrient demand of leaf *l* ($NSink_l$), relative to the total nutrient demand of all leaves ($\Sigma NSink_l$).

$$pN_{i,l} = pN_i * \frac{NSink_l}{\sum_{l=1}^{nl} NSink_l} \quad \text{(S18)}$$

The photosynthetic capacity is limited by either the nitrogen or the phosphorus concentration of the leaf (Jiang *et al.*, 2019), assuming an optimal N:P mass ratio of 15:1 in plant tissues (Aerts & Chapin III, 1999). The photosynthetic capacity of leaf *l* ($Amax_l$, µMol m^{-2} s^{-1}) is calculated with the nutrients allocated to leaf *l* ($pN_{i,l}$, g), its biomass (Bio_l, g), and parameters that denote the maximum photosynthetic capacity ($Amax_0$, µMol m^{-2} s^{-1}), the concentration of nutrient *i* at which photosynthetic capacity is zero ($nmin_i$, g g^{-1}), and the concentration of nutrient *i* at which photosynthetic capacity is maximised ($nmax_i$, g g^{-1}).

$$Amax_l = Amax_0 * \min\left(1, min\left(\frac{pN_{N,l}}{Bio_l * (nmax_N - nmin_N)}, \frac{pN_{P,l}}{Bio_l * (nmax_P - nmin_P)}\right)\right) \quad \text{(S19)}$$

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